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Field crop residue estimate and availability for biofuel production in China

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ABSTRACT

Exploitation of crop residue biomass resources will improve soil quality, future energy security, global carbon balance, and sustainable crop production. The present study was performed in order to evaluate residue quantities and distribution of field crops in the 31 provinces of China mainland with the latest residue indices, based on a province or a region. The annual average total residue in China (750.36 Mt) was composed of 660.76 Mt field residues (88.1%) and 89.60 Mt process residues (11.9%) on an air dried basis, in 2008 and 2009. Grain cereals of rice (200.56 Mt, 30.35%), wheat (145.91 Mt, 19.45%), and maize (153.85 Mt, 23.28%) were the major crops which produced 500.32 Mt field residue, accounting for 73.08% of the total field residue. The annual field residues produced in the 31 provinces varied between 1.26 Mt (Beijing) and 71.59 Mt (Henan). The field residue was distributed in regions according to the order: Northwest China (54.23 Mt, 8.21%) < North China (75.66 Mt, 11.45%) < Southwest China (80.67 Mt, 12.21%) < Northeast China (89.61 Mt, 13.56%) < Central-South China (179.11 Mt, 27.11%) < East China (181.47 Mt, 27.46%). The SCE of the total crop residue was distributed in the top three regions: Central-South China (112.04 Mt)>East China (104.36 Mt)>Northeast China (55.02 Mt). The average residue yield was between 4.14 t ha^{-1} and 8.65 t ha^{-1} and the residue density was between 17.82 t km^{-2} and 224.45 t km^{-2} in these six regions. The total residue quantity for biofuel production could potentially reach 314 Mt (42%), which is composed of the unused (196 Mt) and the directly combusted fuel (118 Mt).

Contents

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1. Introduction

Crop residue has broad traditional usage as a soil amendment, as cooking and heating fuels in farm households, and as animal feed [1]. Concerns about the security and sustainability of fossil fuel use, coupled with advances in biomass conversion technology, have recently raised the possibility of using crop residues as a potential feedstock for bio-fuels and bio-based chemical production [2–5]. China is one of the biggest crop production countries, producing large quantities of crop residue on the one hand, while its energy consumption is increasing rapidly and is comparable to that of the United States as the world's leading emitters of greenhouse gases, on the other hand. As a result, China announced that by 2020, the country would cut its carbon emissions by 40–45% of the 2005 levels. More than 100 biomass power generation plants have been established, which use only crop and forest residues feedstock. Efficient utilization of an equivalent of 300 million tons of crop residue for bioelectricity generation could add renewable energy to China's energy production [6]. The installed capacity of biomass power generation reached 550 MW in 2010 [7]. Furthermore, commercial scale cellulosic ethanol production is ready to be matured by 2014 [8], indicating a greater need for biomass feedstock in the country. Once technology and subsidy for producing ethanol from cellulosic materials are in place, it may be more efficient and the resultant fuel may have lower emissions than grain ethanol [9]. Assessment of crop residue production is important for maintaining carbon sequestration and soil quality and for developing sustainable biomass energy.

The mean field crop production area was 93.92 M ha, which was 77.16% of the total crop harvest area in China in 2008 and 2009, according to the National Bureau of Statistics of China [10,11]. According to a review by Xie et al. [12], previous studies did not enable reaching proper conclusions on the quantity and distribution of the residues produced in the country, although attention has been paid to field crop residue assessment during the last two decades. The main reason for this is that previous researchers used inappropriate crop residue definition and residue index values, since residue weight was calculated from the product of total crop production and residue index. All previous researchers used the same residue index for the same crop across the 31 provinces. This is not appropriate, because China is very large and has temperate, sub-tropic, and tropic regions from the agro-climatic perspective, and humid, semi-humid, semiarid, and arid zones in terms of precipitation. The residue index of a crop should be different between regions where harvest indices are different, resulting from different varieties, soil fertility levels, management, etc. [13]. Furthermore, the values of the residue index used for assessing residues varied to a large extent and were inconsistent for the same crop between researchers [12]. As a result, the field residue indices used in different studies [14,15] evaluated the total accumulated residues of rice, maize, and wheat, as 63.13% of the total field crops harvest area [10,11]. It is also not clear whether the crop process residue was included or separated from the field residue, because the Field Residue Index (*FRI*) and the Process Residue Index (*PRI*) are not well-defined for each crop (see Wang et al. [16]). Lastly, although some of the previous studies addressed the source of the residue index values, we found that the original source was published some 20 years ago [17,18], after comparing the values among the previous studies [12].

Crop residue is consisted of field residue and process residue. Field residue was defined as material left in an agricultural field after the crop was harvested, including stalks and stubble (stems), and leaves. Process residue was defined as material produced in the primary manufacturing process, including rice hull, maize cob, cotton seed hull, peanut husk, sugarcane bagasse, and sugarbeet bagasse. Field crop residue (total residue) consists of field residue and process residue. The Field Residue Index (*FRI*) was the field residue weight to crop production ratio. The Process Residue Index (*PRI*) was the process residue weight to crop production ratio. It is therefore important to determine crop *FRI* and *PRI* values under current production conditions for crop residue assessment. Our group collected the data of harvest indices of field crops in China mainly from the original papers published between 2006 and 2011. We then determined the *FRI* [14–16] and *PRI* [19] from a total of 212 and 126 sample sites, respectively, based on province for rice, wheat, and maize and based on region for the other field crops, after properly defining the *FRI* and *PRI* (Table 1A and Table 1B). The objective of the present paper is to evaluate field crop residue quantity, diversity, and distribution in the 31 provinces of the China mainland, based on the latest *FRI* and *PRI* values of each province or region and crop production data from 2008 to 2009.

2. Methodology

2.1. Regions and provinces of China Mainland

According to the National Bureau of Statistics of China [10,11], the 31 provinces were divided into six regions (Fig. 1), i.e. North China (NC) including Beijing, Hebei, Inner Mongolia, Shanxi, and Tianjin; Northeast China (NEC) including Heilongjiang, Liaoning, and Jilin; East China (EC) including Anhui, Fujian, Jiangsu, Jiangxi, Shandong, Shanghai, and Zhejiang; Central-South China (CSC) including Guangdong, Guangxi, Hainan, Henan, Hubei, and Hunan; Southwest China (SWC) including Guizhou, Sichuan, Tibet, Yunnan, and Chongqing; and Northwest China (NWC) including Gansu, Ningxia, Qinghai, Shaanxi, and Xinjiang provinces.

2.2. Data collection

The field crops covered in this study were exactly matched to those listed in the China Statistical Yearbook [10,11]. Cereal crops were composed of rice (*Oryza sativa* L.), wheat (*Triticum* spp.), maize (*Zea mays* L.), and 'other cereals'. Fibrous crops included

Table 1A
Value taken for Field Residue Index (*FRI*) and Process Residue Index (*PRI*) of the different field crops in North China (NC), Northeast China (NEC), East China (EC), and China.

Residue type	China	NC				NEC			EC							
		Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Shanghai	Jiangsu	Zhejiang	Anhui	Fujian	Jiangxi	Shandong
Field residue																
Rice	1.04	1.10	1.33	0.95	1.00	0.83	1.03	1.03	0.92	1.28	1.24	1.07	1.09	1.14	1.03	1.29
Wheat	1.28	1.29	1.16	1.22	1.25	1.13	1.22	1.25	1.05	1.09	1.41	1.2	1.12	1.34	1.36	1.39
Maize	0.93	0.88	0.85	0.91	1.02	1.16	0.89	0.95	1.02	0.79	0.86	0.82	0.86	0.79	0.81	0.82
Other cereals	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
Beans	1.35	1.36	1.36	1.36	1.36	1.36	1.29	1.50	1.13	1.52	1.52	1.52	1.52	1.52	1.52	1.36
Tubers	0.53	0.42	0.42	0.42	0.42	0.62	0.6	0.6	0.6	0.53	0.53	0.53	0.53	0.58	0.52	0.42
Cotton	2.87	2.62	2.62	2.62	2.62	2.62	2.62	2.62	N/A[a]	3.35	3.35	3.35	3.35	3.35	3.35	2.64
Peanut	0.99	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	1.26	1.26	1.26	1.26	1.08	1.26	0.89
Canola	2.90	N/A [a]	N/A[a]	2.57	2.57	2.57	2.57	N/A[a]	2.57	2.98	2.98	2.98	2.98	2.98	2.98	2.57
Sesame	1.89	N/A[a]	N/A[a]	1.78	1.78	1.78	1.78	1.78	1.78	N/A[a]	2.01	2.01	2.01	2.01	2.01	1.78
Other oil crops	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	N/A	2.63	2.63	2.63	2.63
Jute and ambary	1.73	N/A[a]	N/A[a]	1.73	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	1.73	1.73	N/A[a]	1.73	N/A[a]
Other fibres	6.55	N/A[a]	N/A[a]	6.55	N/A[a]	6.55	N/A[a]	6.55	6.55	N/A[a]	6.55	6.55	6.55	N/A[a]	6.55	N/A[a]
Sugarcane	0.34	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.34	0.34	0.34	0.34	0.34	0.34	N/A[a]
Sugarbeet	0.37	N/A[a]	N/A[a]	0.37	0.37	0.37	0.37	0.37	0.37	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.37
Tobacco	0.66	N/A[a]	N/A[a]	0.71	0.71	0.71	0.71	0.71	0.71	N/A[a]	0.71	0.71	0.72	0.71	0.71	0.71
Process residue																
Rice hull	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.19	0.16	0.19	0.19	0.19	0.20	N/A[a]
Maize cob	0.16	0.14	0.14	0.12	0.14	0.15	0.14	0.15	0.17	0.20	0.20	0.20	0.20	0.20	0.20	N/A[a]
Cotton seed hull	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	N/A[a]	0.47	0.47	0.47	0.47	0.47	0.47	N/A[a]
Peanut husk	0.27	0.27	0.27	0.25	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	N/A[a]
Sugarcane bagasse	0.16	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.16	0.16	0.16	0.16	0.16	0.16	N/A[a]
Sugarbeet bagasse	0.05	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.05	0.05	0.05	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]

[a] N/A means none available, because of no statistics for crop production according to the China Statistical Yearbook [10,11].

Table 1B
Value taken for Field Residue Index (*FRI*) and Process Residue Index (*PRI*) of the different field crops in Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC).

Residue type	CSC						SWC					NWC				
	Henan	Hubei	Hunan	Guangdong	Guangxi	Hainan	Chongqing	Sichuan	Guizhou	Yunnan	Tibet	Shaanxi	Gansu	Qinghai	Ningxia	Xinjiang
Field residue																
Rice	0.97	0.96	0.98	1.07	1.10	1.2	0.91	0.9	1.14	1.14	1.07	0.94	0.84	N/A[a]	0.99	0.74
Wheat	1.29	1.39	1.38	1.27	1.22	N/A[a]	1.08	1.12	1.29	1.2	1.22	1.27	1.26	1.31	1.08	1.36
Maize	0.93	0.84	0.82	0.79	0.8	0.8	0.82	0.84	0.8	0.79	0.81	0.96	0.97	0.96	1.07	1.01
Other cereals	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
Beans	1.36	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.36	1.36	1.36	1.36	1.36	1.33
Tubers	0.42	0.52	0.52	0.58	0.58	0.58	0.49	0.49	0.49	0.49	0.75	0.62	0.62	0.75	0.62	0.62
Cotton	2.41	3.35	3.35	N/A[a]	3.35	N/A[a]	N/A[a]	3.35	3.35	N/A[a]	N/A[a]	2.62	2.62	N/A[a]	N/A[a]	2.85
Peanut	0.86	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	N/A[a]	0.86	0.86	N/A[a]	N/A[a]	0.86
Canola	2.57	2.98	2.98	2.98	2.98	N/A	2.98	2.98	2.98	2.98	2.57	2.57	2.57	2.57	N/A[a]	2.57
Sesame	1.78	2.01	2.01	2.01	2.01	2.01	2.01	2.01	N/A[a]	N/A[a]	N/A[a]	1.78	N/A[a]	N/A[a]	N/A[a]	1.78
Other oil crops	2.63	2.63	2.63	N/A[a]	2.63	N/A[a]	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
Jute and ambary	1.73	1.73	1.73	1.73	1.73	1.73	N/A[a]	1.73	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Other fibres	6.55	6.55	6.55	N/A	6.55	6.55	6.55	6.55	6.55	6.55	N/A[a]	6.55	6.55	N/A[a]	N/A[a]	6.55
Sugarcane	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	N/A[a]	0.34	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Sugarbeet	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.37	N/A[a]	0.37	N/A[a]	N/A[a]	0.37	0.37	N/A[a]	0.37
Tobacco	0.71	0.71	0.85	0.71	0.71	N/A[a]	0.71	0.71	0.71	0.52	N/A[a]	0.71	0.71	0.71	0.71	0.71
Rice hull	0.17	0.20	0.18	0.20	0.19	0.20	0.19	0.19	0.19	0.19	0.19	0.17	0.17	N/A[a]	0.17	0.17
Process residue																
Maize cob	0.12	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.22	0.19	0.14	0.14	0.14	0.14	0.14	0.14
Cotton seed hull	0.47	0.47	0.47	N/A[a]	0.47	N/A[a]	N/A[a]	0.47	0.47	N/A[a]	N/A[a]	0.47	0.47	N/A[a]	N/A[a]	0.47
Peanut husk	0.27	0.27	0.27	0.30	0.27	0.27	0.27	0.27	0.27	0.27	N/A[a]	0.27	0.27	N/A[a]	N/A[a]	0.27
Sugarcane bagasse	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	N/A[a]	0.16	N/A[a]	N/A[a]	N/A[a]	N/A[a]
Sugarbeet bagasse	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]	0.05	N/A[a]	0.05	N/A[a]	N/A[a]	0.05	0.05	N/A[a]	0.05

[a] N/A means none available, because of no statistics for crop production according to the China Statistical Yearbook [10,11].



Fig. 1. Division of China into regions for assessment of crop field residues availability according to crop production (NEC: Northeast China, NC: North China, EC: East China, CSC: Central-South China, SWC: Southwest China).

cotton (*Gossypium* spp.), 'jute and ambary' (*Corchorus* spp. and *Hibiscus cannabinus* L., respectively), and 'other fibers'. Oil crops covered peanut (*Arachis hypogaea* L.), canola (*Brassica* spp.), sesame (*Sesamum indicum*), and 'other oil crops'. Sugar crops were sugarcane (*Saccharum officinarum* L.) and sugarbeet (*Beta vulgaris* L.). All field legume crops and tubers were termed 'beans' and 'tubers', respectively. Tobacco (*Nicotiana tobacco* L.) was also included in this estimation.

Data of field crop production, harvest area, and total area in the 31 provinces in 2008 and 2009 was collected from the China Statistical Yearbook [10,11]. Microsoft Excel 2007 was used to manage data and perform calculations.

2.3. Calculation

The Field Residue Weight (*FRW*) of all field crops, with the exception of sugarcane and sugarbeet, was calculated by Eq. (1) on an air-dried basis. Because the residue of sugarcane was only stalks and of sugarbeet it was only roots, they are presented based on fresh weight in the China Statistical Yearbook, and the *FRW* of these two crops was calculated by Eq. (2) to present the residue weight on an air-dried basis.

$$FRW = ACP \times FRI \quad (1)$$

$$FRW = ACP \times FRI \times (1-M/100) \quad (2)$$

where *FRW* is the field residue weight of a field crop; *ACP* is the Annual Crop Production; *FRI* is a Field Residue Index obtained from Wang et al. [16] (Table 1A, 1B); *M* is moisture, i.e. 70% for sugarcane stalk [12] and 75% for sugarbeet roots [20,21].

Six field crops were used to produce process residues. The quantity of rice hull, maize cob, and peanut husk were estimated by Eq. (3), cotton seed hull by Eq. (4), and sugarcane and sugarbeet bagasses by Eq. (5) to present the residue weight on an air-dried basis.

$$PRW = ACP \times PRI \quad (3)$$

$$PRW = ACP \times (1/GOC-1) \times PRI \quad (4)$$

$$PRW = ACP \times PRI \times (1-M/100) \quad (5)$$

where *PRW* is the Process Residue Weight of a field crop; *ACP* is the Annual Crop Production; *PRI* is a Process Residue Index from Guo et al. [19] (Table 1A, 1B); *GOC* is the Ginning Outturn of Cotton at a value of 0.38 [20]; *M* is moisture which was 70% for sugarcane stalk [12] and 75% for sugarbeet roots [20,21].

Residue yield was the quotient of the residue quantity divided by the harvest area, and residue density of the field crops was the residue yield divided by the total area in each region.

3. Results

3.1. Total quantity of field residue and process residue

The total residue, which was the sum of the field residue and process residue weights of the field crops, was estimated at 751.03 Mt in 2008 and 749.95 Mt in 2009 (Table 2). The annual average total residue (750.36 Mt) was composed of 660.76 Mt field residue (88.1%) and 89.60 Mt process residue (11.9%) (Table 2). Grain cereals of rice (200.56 Mt, 30.35%), wheat (145.91 Mt, 19.45%), and maize (153.85 Mt, 23.28%) were the major crops, which produced 500.32 Mt field residue, accounting for 73.08% of the total field residue in the country. The field residue produced annually varied between 9.18 Mt (1.22%) and 37.38 Mt (4.98%) among the beans, tubers, cotton, peanut, canola, other oil crops, and sugarcane. Sesame, jute and ambary, sugarbeet, and tobacco produced residues varying between 0.13 Mt (0.02%) and 1.95 Mt (0.26%). The process residue was composed of rice hull (35.74 Mt), maize cob (24.96 Mt), cotton seed hull (5.31 Mt), peanut husk (3.98 Mt), sugarcane bagasse (19.18 Mt), and sugarbeet bagasse (0.43 Mt), as averaged for 2008 and 2009 (Table 2).

3.2. Spatial variability in field residues

The distribution of the crop residue in regions and provinces exhibited similar patterns in 2008 and 2009 (Table 3). The annual

Table 2
Estimate of field residue and process residue in the thirty one provinces of China in 2008 and 2009.

Residue type	2008		2009		Mean value	
	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]
Field residue	**660.51**	**100**	**661.27**	**100**	**660.76**	**100**
Rice	198.91	30.11	202.22	30.58	200.56	30.35
Wheat	144.23	19.20	147.66	19.69	145.91	19.45
Maize	154.87	23.48	152.82	23.11	153.85	23.28
Other cereals	19.02	2.53	17.10	2.28	18.06	2.41
Beans	27.51	3.66	26.08	3.46	26.79	3.57
Tubers	15.66	2.09	15.75	3.48	15.71	2.09
Cotton	21.38	3.24	18.27	2.76	19.83	3.00
Peanut	14.19	2.15	14.64	2.21	14.41	2.18
Canola	35.08	4.67	39.67	5.29	37.38	4.98
Sesame	1.10	0.15	1.17	0.16	1.14	0.15
Otheroilcrops	9.16	1.22	9.20	1.23	9.18	1.22
Juteandambary	0.14	0.02	0.12	0.02	0.13	0.02
Otherfibers	3.54	0.47	2.04	0.27	2.79	0.37
Sugarcane	12.66	1.92	11.79	1.78	12.22	1.85
Sugarbeet	0.93	0.14	0.66	0.10	0.79	0.12
Tobacco	1.87	0.25	2.03	0.27	1.95	0.26
Processresidue	**90.52**	**100**	**88.68**	**100**	**89.60**	**100**
Ricehull	35.43	39.14	36.04	40.64	35.74	39.89
Maizecob	25.06	27.68	24.86	28.03	24.96	27.86
Cottonseedhull	5.74	6.34	4.88	5.50	5.31	5.93
Peanuthusk	3.92	4.33	4.03	4.54	3.98	4.44
Sugarcane bagasse	19.86	21.94	18.49	20.85	19.18	21.65
Sugarbeet bagasse	0.50	0.55	0.36	0.41	0.43	0.48
Total residue	**751.03**		**749.95**		**750.36**	

[a] The percentage was calculated within the field residue and process residue for each year.

field residues varied between 1.26 Mt (Beijing) and 71.59 Mt (Henan) among the 31 provinces, which could be divided into four groups. The first group exhibited field residues production ranging between 33.39 Mt (5.05%) and 71.59 Mt (10.83%), and included the eight provinces of Henan, Shandong, Heilongjiang, Jiangsu, Anhui, Sichuan, Hebei, and Hunan. The second group, with annual crop residues between 22.62 Mt (3.42%) and 32.80 Mt (4.96%), consisted of six provinces, i.e. Xinjiang, Jiangxi, Inner Mongolia, Jilin, Guangxi, and Hubei. The third group was composed of ten provinces, i.e. Fujian, Zhejiang, Chongqing, Shanxi, Gansu, Shaanxi, Guizhou, Guangdong, Liaoning, and Yunnan, which produced total residues varying between 7.41 Mt (1.12%) and 18.76 Mt (2.84%) per year. In the last group, each of the provinces produced annual total residues ranging between 1.26 Mt (0.19%) and 3.77 Mt (0.57%). This group was composed of seven provinces, i.e. Beijing, Tianjin, Shanghai, Qinghai, Tibet, Hainan, and Ningxia. The large variation in residue production was due to large differences between provinces in arable land area, crop yield, and farming system.

The field residue, in decreasing order, was NWC < NC < SWC < NEC < CSC < EC. The maize field residue was highest in NC and NEC, reaching 37.53 Mt (49.60%) and 47.15 Mt (52.62%), respectively. In the EC, CSC, and SWC regions, the highest residue production value was found for rice, which reached 72.29 Mt, 69.52 Mt, and 30.70 Mt, respectively. Another important crop, wheat, was 56.15 Mt and 44.06 Mt in EC and CSC, but wheat residue production was highest (16.56 Mt) of all crops in NWC. The highest value of canola residue was harvested as 13.15 Mt in CSC, composing 35.18% of the total.

3.3. Spatial variability in process residue

The annual production of process residue varied between 0.01 Mt and 15.26 Mt on average among the 31 provinces and between 4.78 Mt and 34.50 Mt among the 6 regions (Table 3). There were 7 provinces, i.e. Beijing, Tianjin, Shanghai, Tibet, Gansu, Ningxia, and Qinghai, where the annual process residue varied between 0.01 Mt and 0.51 Mt. In the 11 provinces of Hebei, Inner Mongolia, Shanxi, Liaoning, Zhejiang, Fujian, Hainan, Chongqing, Guizhou, Xinjiang, and Shaanxi, the annual process residue ranged between 0.94 Mt and 3.00 Mt. The other 13 provinces exhibited annual process residue production ranging between 3.62 Mt and

Table 3
Spatial distribution of field and process residue produced in the six regions: North China (NC), Northeast China (NEC), East China (EC), Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC), thirty one provinces in 2008 and 2009.

Region and province	Field residue						Process residue					
	2008		2009		Mean value		2008		2009		Mean value	
	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]	Amount (Mt)	Percent[a]
NC	**77.21**	**11.69**	**74.11**	**11.21**	**75.66**	**11.45**	**6.49**	**7.17**	**6.18**	**6.97**	**6.34**	**7.07**
Beijing	1.27	0.19	1.25	0.19	1.26	0.19	0.13	0.14	0.13	0.15	0.13	0.15
Tianjin	1.71	0.26	1.75	0.26	1.73	0.26	0.2	0.22	0.2	0.22	0.2	0.22
Hebei	34.03	5.15	33.82	5.11	33.92	5.13	2.77	3.06	2.67	3.01	2.72	3.04
Inner Mongolia	28.69	4.34	26.55	4.02	27.62	4.18	2.33	2.58	2.19	2.46	2.26	2.52
Shanxi	11.51	1.74	10.74	1.62	11.13	1.68	1.06	1.17	0.99	1.12	1.03	1.14
NEC	**93.37**	**14.14**	**86.12**	**13.02**	**89.61**	**13.56**	**12.7**	**14.02**	**12.03**	**13.56**	**12.36**	**13.8**
Heilongjiang	45.05	6.82	44.64	6.75	44.84	6.79	5.82	6.43	6.01	6.78	5.92	6.6
Jilin	29.33	4.44	25.43	3.85	27.38	4.14	4.22	4.66	3.66	4.13	3.94	4.4
Liaoning	18.99	2.88	16.05	2.43	17.39	2.63	2.65	2.93	2.36	2.66	2.51	2.79
EC	**180.06**	**27.26**	**182.88**	**27.66**	**181.47**	**27.46**	**18.58**	**20.53**	**18.72**	**21.1**	**18.65**	**20.81**
Shanghai	1.6	0.24	1.66	0.25	1.63	0.25	0.18	0.2	0.18	0.2	0.18	0.2
Jiangsu	46.02	6.97	46.75	7.07	46.38	7.02	3.6	3.98	3.64	4.1	3.62	4.04
Shandong	52.98	8.02	53.08	8.03	53.03	8.03	4.42	4.88	4.35	4.91	4.39	4.89
Zhejiang	9.71	1.47	9.91	1.5	9.81	1.49	1.45	1.6	1.46	1.64	1.45	1.62
Fujian	7.33	1.11	7.48	1.13	7.41	1.12	1.17	1.29	1.18	1.33	1.18	1.31
Jiangxi	22.62	3.42	23.39	3.54	23.01	3.48	4.03	4.45	4.13	4.65	4.08	4.55
Anhui	39.81	6.03	40.6	6.14	40.21	6.08	3.74	4.13	3.78	4.27	3.76	4.2
CSC	**176.94**	**26.79**	**181.29**	**27.41**	**179.11**	**27.11**	**34.76**	**38.4**	**34.24**	**38.6**	**34.5**	**38.5**
Guangdong	14.8	2.24	15.6	2.36	15.2	2.3	4.29	4.74	4.52	5.1	4.41	4.92
Guangxi	23.5	3.56	23.5	3.55	23.5	3.56	15.76	17.41	14.75	16.63	15.26	17.03
Haina	2.63	0.4	2.64	0.4	2.64	0.4	1.15	1.28	1.1	1.24	1.13	1.26
Henan	71.45	10.82	71.72	10.85	71.59	10.83	4.26	4.71	4.28	4.83	4.27	4.77
Hunan	32.44	4.91	34.35	5.19	33.39	5.05	5.18	5.72	5.32	5.99	5.25	5.86
Hubei	32.11	4.86	33.48	5.06	32.8	4.96	4.11	4.54	4.26	4.81	4.19	4.67
SWC	**79.77**	**12.08**	**81.57**	**12.33**	**80.67**	**12.21**	**13.06**	**14.43**	**12.89**	**14.54**	**12.98**	**14.48**
Sichuan	35.82	5.42	36.18	5.47	36	5.45	4.41	4.88	4.43	5	4.42	4.94
Chongqing	10.62	1.61	10.59	1.6	10.61	1.61	1.54	1.7	1.5	1.69	1.52	1.7
Yunnan	18.22	2.76	19.31	2.92	18.76	2.84	5.24	5.79	5.08	5.73	5.16	5.76
Tibet	2	0.3	1.91	0.29	1.95	0.3	0.01	0.01	0.01	0.01	0.01	0.01
Guizhou	13.1	1.98	13.59	2.06	13.35	2.02	1.87	2.07	1.87	2.12	1.87	2.09
NWC	**53.16**	**8.05**	**55.31**	**8.36**	**54.23**	**8.21**	**4.93**	**5.45**	**4.63**	**5.22**	**4.78**	**5.34**
Gansu	11.9	1.8	12.22	1.85	12.06	1.83	0.48	0.53	0.53	0.6	0.51	0.56
Ningxia	3.69	0.56	3.84	0.58	3.77	0.57	0.32	0.36	0.33	0.37	0.33	0.36
Qinghai	2.15	0.32	2.17	0.33	2.16	0.33	0.01	0.01	0.01	0.01	0.01	0.01
Shaanxi	13.51	2.04	13.76	2.08	13.63	2.06	0.92	1.01	0.97	1.09	0.94	1.05
Xinjiang	21.92	3.32	23.32	3.53	22.62	3.42	3.21	3.54	2.8	3.15	3	3.35
Total in China	**660.51**	**100**	**661.27**	**100**	**660.76**	**100**	**90.52**	**100**	**88.68**	**100**	**89.6**	**100**

[a] The percentage was calculated with the division of region and province for each year or the average.

Table 4
Mean annual production of field and process residue of field crops in North China (NC), Northeast China (NEC), East China (EC), Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC) in 2008 and 2009.

Residue type	NC		NEC		EC		CSC		SWC		NWC	
	Amount Mt	Percent[a]	Amount Mt	Percent[a]	Amount Mt	Percent[a]	Amount Mt	Percent[a]	Amount Mt	Percent[a]	Amount Mt	Percent[a]
Field residue	**75.66**	**100**	**89.61**	**100**	**181.47**	**100**	**179.11**	**100**	**80.67**	**100**	**54.23**	**100**
Rice	1.25	1.65	25.01	27.91	72.29	39.84	69.52	38.81	30.70	38.06	1.79	3.30
Wheat	20.72	25.27	1.16	1.14	56.15	28.06	44.06	20.63	7.28	7.77	16.56	30.54
Maize	37.53	49.60	47.15	52.62	20.24	11.15	20.60	11.50	14.83	18.38	13.50	24.89
Other cereals	4.37	5.32	3.25	3.19	2.62	1.31	0.97	0.45	3.16	3.37	3.70	6.27
Beans	3.01	3.67	9.25	9.07	5.02	2.51	3.19	1.49	4.67	4.99	1.66	2.81
Tubers	1.63	1.99	0.88	0.86	2.42	1.21	3.02	1.41	5.38	5.75	2.38	4.03
Cotton	2.22	2.93	0.01	0.01	5.25	2.89	3.85	2.15	0.05	0.06	8.44	15.56
Peanut	1.25	1.65	0.75	1.29	5.21	2.87	6.10	3.41	1.01	1.25	0.09	0.17
Canola	0.65	0.79	0.01	0.01	10.90	5.45	13.15	6.16	9.74	10.40	2.93	4.97
Sesame	0.04	0.05	0.03	0.03	0.25	0.12	0.74	0.35	0.02	0.02	0.05	0.08
Otheroilcrops	2.69	3.28	1.09	1.07	0.44	0.22	2.48	1.16	0.11	0.12	2.38	4.03
Juteandambary					0.03	0.01	0.10	0.05	0.01	0.01		
Otherfibers	0.10	0.12	0.70	0.69	0.17	0.08	0.88	0.41	0.67	0.72	0.28	0.47
Sugarcane					0.26	0.14	9.91	5.53	2.06	2.55		
Sugarbeet	0.19	0.25	0.19	0.21							0.41	0.76
Tobacco	0.02	0.02	0.12	0.12	0.23	0.11	0.53	0.25	0.98	1.05	0.06	0.10
Processresidue	**6.34**	**100**	**12.36**	**100**	**18.65**	**100**	**34.50**	**100**	**12.97**	**100**	**4.78**	**100**
Ricehull	0.23	3.63	4.41	35.68	11.87	63.65	12.97	37.59	5.92	45.64	0.33	6.90
Maizecob	4.99	78.83	7.61	61.57	3.56	19.09	3.29	9.54	3.60	27.76	1.91	39.96
Cottonseed hull	0.65	10.27	0.01	0.08	1.36	7.29	1.01	2.93	0.01	0.08	2.28	47.70
Peanut husk	0.36	5.69	0.24	1.94	1.46	7.83	1.67	4.84	0.22	1.70	0.03	0.63
Sugarcane bagasse					0.40	2.14	15.56	45.10	3.22	24.83		
Sugarbeet bagasse	0.10	1.58	0.10	0.81							0.23	4.81
Total residue	**82.00**		**101.97**		**200.12**		**213.61**		**93.64**		**59.01**	

[a] The percentage was calculated within the field and process residue in each region.

5.92 Mt, with the exception of Guangxi province (15.26 Mt), which was the highest. The process residue produced annually in the 6 regions, in decreasing order, was NWC (4.78 Mt, 5.34%) < NC (6.34 Mt, 7.07%) < NEC (12.36 Mt, 13.80%) < SWC (12.98 Mt, 14.48%) < EC (18.65 Mt, 20.81%) < CSC (34.50 Mt, 38.50%).

3.4. Crop residues in North China

The annual field residue and process residue of the field crops in North China (NC) were estimated at 75.66 Mt and 6.34 Mt, respectively (Table 4). Maize produced the largest quantity of field residue, with 37.53 Mt, which was about half (49.60%) of the total field residue in the region. Maize cob was estimated at 4.99 Mt or 78.83% of the total process residue. Wheat was the second, producing the highest quantity of field residue, with 20.72 Mt (25.27%). The region included five provinces which produced field residue, as follows: Beijing (1.26 Mt) < Tianjin (1.73 Mt) < Shanxi (11.13 Mt) < Inner Mongolia (27.62 Mt) < Hebei (33.92 Mt) (Table 3). The annual process residue varied between 0.13 Mt and 2.72 Mt among the 5 provinces, which exhibited a similar order to that of the field residue.

The annual total SCE in the NC region amounted to 45.63 Mt, which was comprised of 41.82 Mt field residues and 3.81 Mt process residues (Table 5). Maize produced the largest SCE (20.75 Mt), and was 49.6% of the total field residue produced in this region. Wheat produced the second highest SCE, at 11.29 Mt.

Field residue exhibited an annual yield between 1.77 t ha^{-1} and 6.11 t ha^{-1} and the density was between 0.01 t km^{-2} and 24.71 t km^{-2} among field crops in the NC region (Table 6). Maize and rice produced a much higher field residue density (24.71 t km^{-2} and 13.65 t km^{-2}, respectively) than any of the other crops. Rice (6.11 t ha^{-1}), sugarbeet (5.85 t ha^{-1}), wheat (5.42 t ha^{-1}), and maize (5.23 t ha^{-1}) produced higher yields of field residue than any of the other crops.

3.5. Crop residues in Northeast China

The annual average production of field residue and process residue was estimated at 101.97 Mt and 12.36 Mt, respectively, in Northeast China (NEC) (Table 4). A major portion (80.53%) of the field residue was produced from maize (47.15 Mt, 52.62%) and rice (25.01 Mt, 27.91%). Maize cob and rice hull were estimated at 7.61 Mt and 4.41 Mt, accounting for 61.57% and 35.68% of the total process residue in the region, respectively. The region included three provinces which produced field residue, as follows: Liaoning (16.05 Mt) < Jilin (25.43 Mt) < Heilongjiang (44.64 Mt) (Table 3).

The annual total SCE in the NEC region amounted to 55.02 Mt, which was comprised of 48.01 Mt field residues and 7.01 Mt process residues (Table 5). Maize produced the largest SCE (26.07 Mt), and was 54.3% of the total field residue produced in this region. Rice produced the second highest SCE at 11.55 Mt.

Field residue exhibited an annual yield between 1.73 t ha^{-1} and 6.62 t ha^{-1} and density between 0.01 t km^{-2} and 59.55 t km^{-2} among field crops in the NEC region on average in 2008 and 2009 (Table 6). Rice and maize produced much higher field residue density (31.59 t km^{-2} and 59.55 t km^{-2}, respectively) than each of the other crops. Rice (6.62 t ha^{-1}), cotton (5.62 t ha^{-1}), maize (5.28 t ha^{-1}), and sugarbeet (4.34 t ha^{-1}) produced a relatively high field residue yield compared to the other crops. Five crops produced process residue, of which maize cob exhibited the highest density (9.61 t km^{-2}).

Table 5
Lower Heating Value Ratio (LHVR) and mean annual Standard Coal Equivalence (SCE) of field and process residue of field crops in North China (NC), Northeast China (NEC), East China (EC), Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC) in 2008 and 2009

Residue type	LHVR	NC		NEC		EC		CSC		SWC		NWC	
		SCE Mt	Percent[a]	SCE Mt	Percent[a]	SCE Mt	Percent[a]	SCE Mt	Percent[a]	SCE Mt	Percent[a]	SCE Mt	Percent[a]
Field residue		**41.82**	**100**	**48.01**	**100**	**94.45**	**100**	**92.73**	**100**	**41.96**	**100**	**30.26**	**100**
Rice	**0.462**	0.58	1.39	11.55	24.06	33.40	35.36	32.12	34.64	14.18	33.79	0.83	2.74
Wheat	**0.545**	11.29	27.00	0.63	1.31	30.60	32.40	24.01	25.89	3.97	9.46	9.03	29.84
Maize	**0.553**	20.75	49.62	26.07	54.30	11.19	11.85	11.39	12.28	8.20	19.54	7.47	24.69
Othercereals	**0.545**	2.38	5.69	1.77	3.69	1.43	1.51	0.53	0.57	1.72	4.10	2.02	6.68
Beans	**0.652**	1.96	4.69	6.03	12.56	3.27	3.46	2.08	2.24	3.04	7.24	1.08	3.57
Tubers	**0.432**	0.70	1.67	0.38	0.79	1.05	1.11	1.30	1.40	2.32	5.53	1.03	3.40
Cotton	**0.625**	1.39	3.32	0.01	0.02	3.28	3.47	2.41	2.60	0.03	0.07	5.28	17.45
Peanut	**0.541**	0.68	1.63	0.41	0.85	2.82	2.99	3.30	3.56	0.55	1.31	0.05	0.17
Canola	**0.610**	0.40	0.96	0.01	0.02	6.65	7.04	8.02	8.65	5.94	14.16	1.79	5.92
Sesame	**0.529**	0.02	0.05	0.02	0.04	0.13	0.14	0.39	0.42	0.01	0.02	0.03	0.10
Otheroilcrops	**0.584**	1.57	3.75	0.64	1.33	0.26	0.28	1.45	1.56	0.06	0.14	1.39	4.59
Juteandambary	**0.600**					0.02	0.02	0.06	0.06	0.01	0.02		
Otherfibers	**0.546**	0.05	0.12	0.38	0.79	0.09	0.10	0.48	0.52	0.37	0.88	0.15	0.50
Sugarcane	**0.494**					0.13	0.14	4.90	5.28	1.02	2.43		
Sugarbeet	**0.205**	0.04	0.10	0.04	0.08							0.08	0.26
Tobacco	**0.550**	0.01	0.02	0.07	0.15	0.13	0.14	0.29	0.31	0.54	1.29	0.03	0.10
Processresidue		**3.81**	**100**	**7.01**	**100**	**9.91**	**100**	**19.31**	**100**	**7.17**	**100**	**2.85**	**100**
Rice hull	**0.490**	0.11	2.89	2.16	30.81	5.82	58.73	6.36	32.94	2.90	40.45	0.16	5.61
Maize cob	**0.610**	3.04	79.79	4.64	66.19	2.17	21.90	2.01	10.41	2.20	30.68	1.17	41.05
Cotton seed hull	**0.600**	0.39	10.24	0.01	0.14	0.82	8.27	0.61	3.16	0.01	0.14	1.37	48.07
Peanut husk	**0.590**	0.21	5.51	0.14	2.00	0.86	8.68	0.99	5.13	0.13	1.81	0.02	0.70
Sugarcane bagasse	**0.600**					0.24	2.42	9.34	48.37	1.93	26.92		
Sugarbeet bagasse	**0.570**	0.06	1.57	0.06	0.86							0.13	4.56
Total residue		**45.63**		**55.02**		**104.36**		**112.04**		**49.13**		**33.11**	

[a] The percentage was calculated within the field and process residue in each region.

Table 6
Mean yield residue and density of the different field crops produced in North China (NC), Northeast China (NEC), East China (EC), Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC) annually in 2008 and 2009.

Residue type	NC		NEC		EC		CSC		SWC		NWC	
	Yield t ha^{-1}	Density t km^{-2}	Yield t ha^{-1}	Density t km^{-2}	Yield t ha^{-1}	Density t km^{-2}	Yield t ha^{-1}	Density t km^{-2}	Yield t ha^{-1}	Density t km^{-2}	Yield t ha^{-1}	Density t km^{-2}
Field residue	**4.32**	**49.82**	**4.52**	**113.17**	**5.98**	**224.45**	**8.65**	**176.29**	**4.14**	**34.66**	**4.60**	**17.82**
Rice	6.11	0.82	6.62	31.59	7.37	89.41	6.26	68.43	6.90	13.19	6.35	0.59
Wheat	5.42	13.65	3.78	1.46	6.92	69.44	7.00	43.37	3.34	3.13	4.62	5.44
Maize	5.23	24.71	5.28	59.55	4.90	25.03	4.68	20.28	3.80	6.37	5.11	4.44
Beans	1.77	1.98	1.84	11.68	2.60	6.20	2.81	3.14	3.03	2.01	2.65	0.54
Tubers	1.47	1.07	1.89	1.11	2.52	2.99	2.09	2.97	1.59	2.31	1.86	0.78
Cotton	2.96	1.46	5.62	0.02	3.50	6.50	3.34	3.79	2.96	0.02	5.53	2.77
Peanut	2.94	0.82	1.83	0.96	3.93	6.44	3.42	6.00	2.59	0.44	2.53	0.03
Canola	2.63	0.43	3.64	0.01	5.57	13.48	5.09	12.94	5.25	4.19	4.65	0.96
Jute and ambary	3.67	0.01			6.36	0.04	5.77	0.10	3.30	0.01		
Sugarcane					5.71	0.32	7.53	9.76	6.12	0.88		
Sugarbeet	5.85	0.19	4.34	0.37							9.38	0.21
Tobacco	1.84	0.01	1.73	0.16	1.61	0.29	1.55	0.52	1.26	0.42	1.49	0.02
Process residue	**0.36**	**4.17**	**0.62**	**15.61**	**0.61**	**23.06**	**0.68**	**33.96**	**0.67**	**5.57**	**0.41**	**1.57**
Rice hull	1.13	0.15	1.17	5.57	1.21	14.68	1.17	12.77	1.33	2.54	1.19	0.11
Maize cob	0.70	3.29	0.85	9.61	0.86	4.40	0.75	3.24	0.92	1.55	0.72	0.63
Cotton seedhull	0.86	0.43	1.64	0.01	0.91	1.68	0.87	0.99	0.68	0.01	1.50	0.75
Peanut husk	0.86	0.24	0.57	0.30	1.10	1.80	0.94	1.65	0.55	0.09	0.80	0.01
Sugarcane bagasse					8.96	0.50	11.81	15.31	9.61	1.38		
Sugarbeet bagasse	2.05	0.07	1.52	0.13							3.29	0.07

3.6. *Crop residues in East China*

The annual field residue and process residue production in East China (EC) was estimated at 181.47 Mt and 18.65 Mt, respectively (Table 4). 70.1% of the field residue was derived from rice (72.29 Mt, 39.84%) and wheat (56.15 Mt, 28.06%). Maize and canola were the third and fourth largest crops, and produced field residues of 20.24 Mt (11.15%) and 10.90 Mt (5.45%), respectively.

Process residue was mainly rice hull with 11.87 Mt or 63.65% of the process residue. The region included seven provinces which produced crop residue, as follows: Shanghai (1.63 Mt) < Fujian (7.41 Mt) < Zhejiang (9.81 Mt) < Jiangxi (23.01 Mt) < Anhui (40.21 Mt) < Jiangsu (46.38 Mt) < Shandong (53.03 Mt) (Table 3).

The annual total SCE in the EC region amounted to 104.36 Mt, which was comprised of 94.45 Mt field residues and 9.91 Mt process residues (Table 5). Rice and wheat produced the most SCE (33.40 Mt and 30.60 Mt, respectively), which was 67.8% of the total field residue produced in this region.

Field residue exhibited an annual yield between 1.61 t ha^{-1} and 7.37 t ha^{-1} and density was between 0.04 t km^{-2} and 89.41 t km^{-2} among field crops on average between 2008 and 2009 (Table 6). Rice and wheat produced a much higher field residue density (89.41 t km^{-2} and 69.44 t km^{-2}, respectively) than each of the other crops. Rice (7.37 t ha^{-1}), wheat (6.92 t ha^{-1}), jute and ambary (6.36 t ha^{-1}), sugarcane (5.71 t ha^{-1}) and canola (5.57 t ha^{-1}) produced a relatively high field residue yield. Five crops produced process residue, of which rice hull exhibited the highest density (14.68 t km^{-2}), and sugarcane bagasse yield was estimated at the highest value of 8.96 t ha^{-1}.

3.7. Crop residues in Central-South China

The annual average production of the residues was composed of 179.11 Mt field residue and 34.50 Mt process residue in Central-South China (CSC) (Table 4). Rice and wheat produced the highest field residue of 69.52 Mt (38.81%) of the field residue in CSC) and 44.06 Mt (20.63%). The largest process residue included rice hull of 12.97 Mt (37.59%) and sugarcane bagasse of 15.56 Mt (45.10% of process residue in CSC). The region included six provinces which produced field residue as follows: Hainan (2.64 Mt) < Guangdong (15.20 Mt) < Guangxi (23.50 Mt) < Hubei (32.80 Mt) < Hunan (33.39 Mt) < Henan (71.59 Mt) (Table 3).

The annual total SCE in the CSC region amounted to 112.04 Mt, which wasd comprised of 92.73 Mt field residues and 19.31 Mt process residues (Table 5). Rice and wheat produced the most SCE (32.12 Mt and 24.01 Mt, respectively), which was 60.5% of the total field residue produced in this region. Rice hull and sugarcane bagasse produced the most SCE (6.36 Mt and 9.34 Mt, respectively), which was 81.3% of the total process residue produced in this region.

The CSC region produced a field residue yield of 8.65 t ha^{-1} and density of 176.29 t km^{-2} (Table 6). Field residue exhibited an annual average of between 0.36 kg and 248.80 kg $person^{-1}$, yield between 1.55 t ha^{-1} and 7.53 t ha^{-1}, and density between 0.10 t km^{-2} and 68.43 t km^{-2} among the field crops in the CSC region. Rice and wheat produced a much higher field residue density (68.43 t km^{-2} and 43.37 t km^{-2}, respectively) than any of the other crops. Sugarcane (7.53 t ha^{-1}), wheat (7.00 t ha^{-1}), rice (6.26 t ha^{-1}), jute and ambary (5.77 t ha^{-1}), and canola (5.09 t ha^{-1}) produced a relatively high field residue yield. Five crops produced process residue, of which sugarcane bagasse exhibited the highest density (15.31 t km^{-2}), and its yield was estimated at the highest value of 11.81 t ha^{-1}.

3.8. Crop residues in Southwest China

The field residue and process residue was composed of 80.67 Mt and 12.97 Mt annually in Southwest China (SWC) (Table 4). About 56.44% of the field residue production was produced from rice (38.06%, 30.70 Mt) and maize (18.38%, 14.83 Mt). Rice hull was the largest quantity of process residue with 5.92 Mt or 45.64%, followed by maize cob of 3.60 Mt (27.76%). The three main crops, excluding rice, wheat and maize, were tubers as 5.38 Mt, canola as 9.74 Mt, and sugarcane as 2.06 Mt, composing 18.70% of the total crop residues in SWC. The field residue in Tibet was 1.95 Mt, not including a very low amount of process residue. The region included five provinces which produced field residue, as follows: Tibet (1.95 Mt) < Chongqing (10.61 Mt) < Guizhou (13.35 Mt) < Yunnan (18.76 Mt) < Sichuan (36.00 Mt) (Table 3).

The annual total SCE in the SWC region amounted to 49.13 Mt, which was comprised of 41.96 Mt field residues and 7.17 Mt process residues (Table 5). Rice and maize produced the most SCE (14.18 Mt and 8.20 Mt, respectively), which was 53.3% of the total field residue produced in this region.

The SWC region exhibited a field residue yield of 4.14 t ha^{-1} and a density of 176.29 t km^{-2} on average in 2008 and 2009 (Table 6). Field residue exhibited an annual average yield between 1.26 t ha^{-1} and 6.90 t ha^{-1} and a density between 0.01 t km^{-2} and 13.19 t km^{-2} among the field crops in SWC (Table 6). Rice produced a much higher field residue density (13.19 t km^{-2}) than any of the other crops. Rice (6.90 t ha^{-1}), sugarcane (6.12 t ha^{-1}), and canola (5.25 t ha^{-1}) produced a relatively high field residue yield. Five crops produced process residue, of which rice hull exhibited the highest density (2.54 t km^{-2}).

3.9. Crop residues in Northwest China

The annual field residue and process residue of the field crops was estimated at 54.23 Mt and 4.78 Mt in Northwest China (NWC) (Table 4). Residues from maize (13.50 Mt) and wheat (16.56 Mt) constituted 55.43% of the field residue. Process residue was mainly maize cob, which was estimated at 1.91 Mt or 39.96%. However, oil crops and cotton were widely distributed in NWC, and made up nearly 24.81% of this region, with cotton being the most of the six regions (Table 4). The region included five provinces which produced crop residues, as follows: Qinghai (2.16 Mt) < Ningxia (3.77 Mt) < Gansu (12.06 Mt) < Shaanxi (13.63 Mt) < Xinjiang (22.62 Mt) (Table 3).

The annual total SCE in NWC amounted to 33.11 Mt, which was comprised of 30.26 Mt field residues and 2.85 Mt process residues (Table 5). Wheat produced the largest SCE (9.03 Mt), which was 29.8% of the total field residue produced in this region.

Field residue exhibited an annual average yield between 1.49 t ha^{-1} and 9.38 t ha^{-1} and density between 0.02 t km^{-2} and 5.44 t km^{-2} among the field crops in the NWC region (Table 6). Wheat and maize produced a much higher field residue density (5.44 t km^{-2} and 4.44 t km^{-2}, respectively) than each of the other crops. Sugarbeet (9.38 t ha^{-1}), rice (6.35 t ha^{-1}), cotton (5.53 t ha^{-1}) and maize (5.11 t ha^{-1}) produced a relatively high field residue yield. Five crops produced process residue, of which maize cob and cotton seed hull exhibited the highest density (0.63 t km^{-2} and 0.75 t km^{-2}, respectively).

4. Discussion

4.1. Residue quantity of field crops

This report is one of the series of crop residue assessments and availability for biofuel production in China carried out by our group. It presents the most precise assessment of residue quantity of field crops and its regional and provincial distributions in China to date. We not only used the latest crop production statistic data, but also the latest residue indices. Our previous studies exhibited considerable variations in *FRI* [16] and *PRI* [19] among provinces (or regions) for the same crop. This investigation is the first to evaluate crop residues with residue indices based on a province or a region. One of the latest assessments of agricultural residues

Table 7
Field Residue Indices (*FRI*) in the literature used to estimate residues of rice, maize, wheat, and cotton in China.

Crop	Field Residue index	Literature
Rice	0.6	[39]
	0.62	[40]
	0.623	[2,22,33,34,41–45]
	0.68	[23,36,46]
	0.9	[32]
	0.97	[47]
	1.0	[48–53]
Maize	1.2	[32]
	1.25	[23,36,46]
	1.37	[47]
	2.0	[2,22,33,34,39–45,48–53]
Wheat	0.73	[23,36,46]
	1.03	[47]
	1.0	[51]
	1.1	[32,48,50,52,53]
	1.3	[39]
	1.366	[2,22,33,34,41–45,49]
	1.37	[40]
Cotton	3.0	[2,33,34,39,41,42,44,48,50,51,53]
	5.51	[23,36,46]
	9.2	[32]

produced in 2008 was reported by Zhou et al. [22], who underestimated rice residue (119.55 Mt) and overestimated maize residue (331.82 Mt) at a rate of 96% and 46%, respectively, due to the lower *FRI* (0.623) for rice and the higher *FRI* (2) for maize, compared with the findings of this study and the *FRI* we determined [17,18] (Table 7). Rice residue (205 Mt) was underestimated and maize residue (265 Mt) was overestimated at a rate of 16% and 33%, respectively, by Tian et al. [23] and IOMOA [24] for its production in 2009. The *FRI* values for rice, varying between 0.6 and 0.68 in 14 of 21 publications published between 1998 and 2011, are obviously lower, whereas the *FRI* value of 2.0 in 16 of 21 publications are obviously higher for maize (Table 1), compared with the *FRI* varying between 0.74 and 1.33 and averaging 1.04 for rice among 30 provinces, and *FRI* varying between 0.93 and 1.30 and averaging 1.07 among 31 provinces based on sample sizes of 41 and 30, respectively, originally published between 2006 and 2011 [14,16] (Table 7).

4.2. *Crop residue as a soil amendment*

Retention of crop residue is essential for carbon sequestration, maintaining soil quality and reducing soil erosion risks. Indiscriminate removal of residue can lead to a decline in soil quality, with long-lasting adverse impacts on the environment. The residue requirement for soil erosion control depends on soil erodibility, rainfall erosion, terrain characteristics, land use, farming system, tillage methods, and other soil management processes [1]. Several studies exhibited different amounts of residue that must be retained in soil. Metzger et al. [25] reported that the US Department of Agriculture recommends that about a quarter of the crop residues be left on the fields to prevent soil erosion and return some nutrients to the soil. This must be balanced against carbon sequestration needs. According to McAloon et al. [26], Nelson [27], and Kim and Dale [28], 20–40% of the maize residue produced in the US Maize Belt can be removed for biofuel production. Sheehan et al. [29] concluded that 40% of the residue can be collected under continuous maize production and mulch till, compared with 70% under no-till while keeping erosion risks below the tolerable limit. McCool et al. [30] showed that a 30% removal rate resulted in 93% soil cover after residue harvest.

The current soil organic carbon density in China′s cropland is relatively low due to long-term carbon loss from soil. Crop straw return is one of the most promising measures for reversing the process of stimulating soil carbon loss and increasing carbon sequestration, according to Lu et al. [31] who reviewed the long-term field experimental data in China on soil carbon changes under nitrogen fertilizer application, straw return, and no till practices. However, it was estimated that a total of 235 Mt field residue, i.e. 29% of the total residue, was incorporated into soil in 2009. This included 133 Mt residue left inevitably as leaves, stubble, etc. in fields when it was collected and 102 Mt residue in 23.9 million hectares of crop area which was incorporated mechanically into soil according to t IOMOA [24]. This indicates that residue incorporated into the soil does not meet the demand of soil erosion control and maintenance of quality. We strongly recommend increasing the amount of residue retained in soil in China. Use of the residue for biofuel production must be assessed objectively with a holistic approach and long-term perspective [1,3].

4.3. *Competitive usage and availability for biofuel production*

Besides soil amendment, crop residue has been used in China for different purposes such as fuel, animal feed, paper industry, substrates for mushroom cultivation, etc. An amount of 129 Mt (16%) crop residue was used as fuel directly combusted by farmers, biomass power plants, etc. In 2009, 211 Mt residue was used as feed, 15 Mt as industrial raw materials including paper making, 16 Mt for mushroom cultivation, and 215 Mt (26%) residue was burned in fields or was wasted in the countryside [24]. As a result of our finding according to the utilization percentage of crop residue of IOMOA [24], the unused residue of field crops which was burned in fields or abandoned in the countryside was 196 Mt (26%) in total in the country (Fig. 2). This estimate of unused residue is lower than that (215 Mt) of IOMOA [24], who overestimated the field crop residue (821 Mt) compared to our finding (750 Mt). Therefore, the total residue quantity for biofuel production in the country could be composed of the unused residue and that used for directly combusted fuel which was 314 Mt (42%). However, many indices such as the quantity per capita, yield, density, harvest duration, traffic, and condition influence the risk of residue procurement for energy application [32–36]. Crop residue availability differs between regions in China based on the findings of this study, the literature [24,37,38] and communication with local experts (Table 8). Subsequent manuscripts on crop residue resources and their availability for biofuel in each region in detail will be published, based on provincial data.

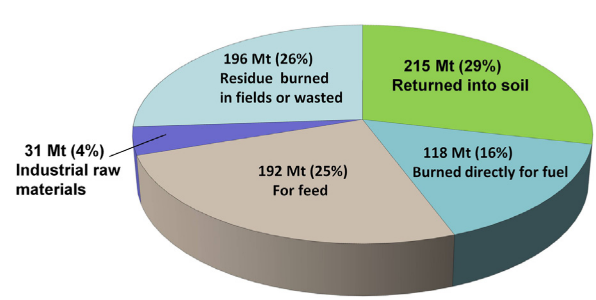


Fig. 2. Distribution of different utilization percentages of crop residue in China annually in 2008 and 2009.

Table 8
Characteristics favoring the use of field residue for fuel production in North China (NC), Northeast China (NEC), East China (EC), Central-South China (CSC), Southwest China (SWC), and Northwest China (NWC) according to the resource availability.

Characteristics	NC	NEC	EC	CSC	SWC	NWC	Reference
Residue density	+	++	++++	+++	+		present study
Surplus amount	+	+	++	++	++		[24]
Harvest duration	+	+++				+++	[38]
Traffic condition	++	+++	++	+		++	[37]
First favorable crop	maize, wheat	maize, rice	rice, wheat, maize	rice, wheat, maize	rice		present study
Secondary favorable crop		beans	canola	canola			present study

4.4. *The indistinct definition of crop residue and the improper residue indices in the previous reports*

The distinct definition and classification system of crop residue among previous researchers led to big differences in the evaluation of crop residue resources in China. Although it was called "crop residue" in the previous research literature, it included only "field residue" but not process residue, such as rice husk, maize cob, sugar beet bagasse and so on.

The Field Residue Index (*FRI*) which was used previously exhibited a large variation ranging between 0.6–1.0 for rice, 1.2–2.0 for maize, and 0.73–1.37 for wheat. The largest variation, ranging between 3.0–9.2, was found in cotton residue assessment (Table 7). It led to the huge difference in the assessment of crop residue resource, because of the large variation in the *FRI* values. As crop genetic improvement are developed, the harvest index increases and residue index decreases in general. The most obvious example is maize for which the *FRI* value of maize was 2 some 20 years ago. During the past two decades maize was one that improved genetically in the most intensive way, so that it *FRI* value was far less than 2.

5. Conclusion

Due to the use of proper crop residue definition and indices, this study presents a relatively precise assessment of residue quantity of field crops and its geographical distribution in China compared with previous literature. It will help policy makers and investors to optimize the utilization of the crop residue resource. A field residue of 218 Mt was retained in the soil, accounting for 29% of the total (Fig. 2). We recommend increasing residue incorporation into soil in order to maintain soil quality and reduce soil erosion risks. The use of soil residue for other purposes, such as biofuel production, must be assessed objectively with a holistic approach and long-term perspective. Currently, after it met the use for animal feed, paper industry, mushroom cultivation, etc., a total of 314 Mt residue was estimated as a potential for biofuel production, which is 42% of the total residue of field crops in the country. However, many limiting factors increase the risk of residue procurement for energy application and require further investigation.

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